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RESEARCH PAPER

Survey of damaging pests and preliminary assessment of forest health risks to the long term success of *Pinus radiata* introduction in Sichuan, southwest China

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Abstract: *Pinus radiata* was introduced to the summer rainfall environments of Sichuan Province, China in the 1990s as a part of an afforestation program for soil and water conservation in the arid and semi-arid river valley area of Aba Prefecture. Within this region a total area of 26 000 ha have been identified through climate matching as suitable and a further 63 000 ha potentially suitable for environmental plantings of *P. radiata*. The plantations are being established in widely separated small patches on steep and degraded slopes along the dry river valley. The newly introduced *P. radiata* are exposed to two kinds of forest health risks: they may be attacked by (a) indigenous pathogens and pests against which they may not possess any resistance or (b) by inadvertently introduced foreign pests or pathogens. This paper presents a survey of the potential damaging pests and a preliminary assessment of forest health risks facing the *P. radiata* plantations over a much longer time-frame than the initial phase of introduction and early plantation establishment. An empirical approach was adopted to evaluate forest health risks by a combination of literature review, examination of historical records of pest and disease outbreaks in the surrounding coniferous forests, field surveys and inspections, specimen collection and identification, and most importantly, expert analysis of the likelihood of attack by specific pests and pathogens and the subsequent impact of such attacks. The assessment identified some specific forest health risks to the long-term success of *P. radiata* introduction in this area. These risks are closely associated with the indigenous pests and pathogens of the two native pine species, *P. tabulaeformis* and *P. armondii* since these pests and pathogens are considered more likely to establish on *P. radiata* over time. Exotic pests and pathogens are of a quarantine concern at present. Based on the results of assessment, recommendations are provided to improve forest vigour and to reduce the forest health risks posed by indigenous as well as exotic pests and pathogens to the introduced *P. radiata*. Ways to increase the ability to manage the forest health risks once a particular pest infestation and disease eventuates are also recommended. Although detrimental to the survival and growth of the introduced *P. radiata*, the impact of identified forest health risks are not considered to be fatal to the long term success of *P. radiata* in this area.

Keywords: *Pinus radiata;* species introduction; dry river valley; forest health risks

Introduction

Originating from a very restricted natural distribution along the central coast of California, United States and the Cedros and Guadalupe islands off Baja California in Mexico, *Pinus radiata* (D. Don) has been introduced over the last 150 years to many parts of the world as an exotic species for afforestation (Scott 1960; Lavery and Mead 1998; Rogers 2002; Rogers et al. 2006). It has now become one of the most widely planted exotic pine species in the world, particularly in winter or uniform rainfall environments of the Southern Hemisphere, mostly with a Mediterranean climate (Lewis and Ferguson 1993; Lavery and Mead 1998). In Australia, Chile, New Zealand and South Africa, it is a mainstay of the forest economy serving domestic markets and generating income from exports (Lewis and Ferguson 1993; Lavery and Mead 1998; Toro et al. 1999; Turner et al. 1999). In the Northern Hemisphere, the only large scale plantations are in the Spanish Basque Region between latitude 40° and 44°N with a Mediterranean climate (Lavery and Mead 1998). Besides these countries, *P. radiata* has also been planted at a smaller scale or in species introduction experiments in many other countries in

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both Hemispheres. Currently the worldwide *P. radiata* plantation estate exceeds 4 million hectares and is still expanding (Lavery and Mead 1998; Rogers 2002).

Pinus radiata was first introduced to the summer rainfall environments of Sichuan Province, China in 1990 as a part of research to select the most suitable species for afforestation for soil and water conservation in the arid and semi-arid river valley area of Aba Prefecture (Bi et al. 2003). Within this region a total area of 26 000 ha has been identified through climate matching as suitable and a further 63 000 ha potentially suitable for environmental plantings of *P. radiata* (Yan et al. 2006). Over the past 15 years, local foresters and scientists have made a great effort to improve nursery practices, site preparation and planting techniques for the exotic species and set up silvicultural experiments on fertilization, spacing and pruning to improve stand management of the young plantations (Wu et al. 2005). Among a number of native as well as exotic species that have been tested in planting trials in this area, *P. radiata* had the lowest mortality, the best growth rates and the highest biomass production (Bi et al. 2003; Wu et al. 2005; Pan et al. 2005).

Although the comparative growth performance of *P. radiata* is observed during early plantation growth and establishment, its superiority has made it the species of choice for environmental plantings (Wu et al. 2005). Several experimental plantations of *P. radiata* with a total area of more than 120 ha had been established by year 2000 (Bi et al. 2003). Since then the total planting area has been expanding. These plantations will play an important part of the shelterbelt forest program along the upper reaches of Yangtze River (Anonymous 1995; Li 2004). Furthermore *P. radiata* is considered to be the species potentially suitable for environmental planting over many degraded lands to reduce soil erosion in southwest China (Wu et al. 2005; Yan et al. 2006).

However, the initial promising growth performance of *P. radiata* can not be taken as a guarantee for its long term success in the dry river valley area decades into the future. Newly introduced exotic species usually experience an initial period with few pest and disease problems, while pathogens and pests build up and local pests take time to adapt themselves to the new host (FAO 2001; Nair 2001). A number of cases where the introduction of *P. radiata* have experienced major problems or completely failed following seemingly successful early growth are described in Scott (1960), Lavery (1986) and Lavery and Mead (1998). Similar cases were also found in eastern China where disease and pest attacks predisposed by damp summer heat were considered to be the major causes of failure of earlier attempts of introducing *P. radiata* to warm temperate and subtropical climate zones in the 1970s and 1980s (Wu 1983; Yan et al. 2006).

In general, plantations of exotic species are exposed to two sources of damaging biotic agents: they may be attacked by an indigenous pathogen or pest against which the trees may not possess any resistance or by an inadvertently introduced exotic pathogen or pest (Bakshi 1976; FAO 2001; Dalin and Björkman 2006). In the literature on exotic plantations in both tropical and temperate zones there are abundant examples (FAO 2001; Nair 2001). For *P. radiata* in particular; an example of the first type where indigenous pests become adapted to the exotic pine is *Ormiscodes cinnamomea* Feisth., a large Saturniid moth that has become a defoliator of *P. radiata* in Chile (Ciesla 1997). A good example of the second type is the European wood wasp (*Sirex noctilio* F.) which, with its symbiotic fungus *Amylostereum areolatum* (Fr.) Boidin, can cause widespread mortality in stands of any age in New Zealand and Australia (Madden 1988; Eldridge and Simpson 1987; Burgess and Wingfield 2001). It has also become a major concern in *P. radiata* plantations in South Africa following its introduction in the early 1990s (Tribe 1995; Tribe and Cillié 2004). Native to southern Europe and North Africa, where it causes little or no economic damage, the insect was probably introduced on unprocessed pine logs imported from Europe into New Zealand and subsequently appeared in *P. radiata* plantations in Australia (Gilbert and Miller 1952). Another example is the fungi, *Dothistroma septospora* (Dorog.) M. Morelet, innocuous on *P. radiata* in its indigenous home in California, but now the cause of serious damage in plantations in all major *P. radiata* growing countries (Gibson 1972; Bakshi 1976; Liebhold et al. 1995).

There has been limited evidence of pests and diseases in the young *P. radiata* plantations in the dry river valley area of Aba (Bi et al. 2003; Zhou et al. 2005; Xiao et al. 2006). However, forest health risk is expected to become greater as many indigenous pests and pathogens can adapt to an exotic host over time. As stands mature a proportion of the trees become suppressed and die. The suppressed trees are often more susceptible to pathogens and pests than are dominant trees, presenting an increased forest health risk to the whole stand. In addition, forest health risk might also increase with possibly further expansions of *P. radiata* plantings in other climatically suitable areas of Sichuan and southwest China (see Yan et al. 2006). For the success of *P. radiata* introduction in the summer rainfall environments of China, it is necessary to survey the potential damaging pests and assess forest health risks posed by the indigenous as well as exotic insects and pathogens to the newly introduced tree species decades into the future.

This paper presents such a survey and assessment for *P. radiata* plantations in the dry river valley area beyond the initial phase of introduction and early establishment. Because *P. radiata* has been planted in the area for a relatively short period of time, an empirical approach was adopted to evaluate forest health risks by a combination of literature review, examination of historical records of pest and disease outbreaks in the surrounding coniferous forests, field surveys and inspections, specimen collection and identification, and most importantly, expert analysis of the likelihood of attack by specific pests and pathogens and the subsequent impact of such attack. Based on the results of assessment, recommendations are provided to reduce the susceptibility of the *P. radiata* plantations to indigenous as well as exotic pests and pathogens. Ways to manage the forest health risks once a particular pest infestation and disease eventuates are also recommended.

The study area

The Minjiang River is one of the four principal tributaries of the

Yangtze River. Its upper reaches flow over 340 km through a highly mountainous region from the southeast of Qinghai and the Tibet plateau down to the Sichuan basin (Fan et al. 2006; Li et al. 2006). High and steep mountain peaks towering 1 500–3 500 m above the deep river valleys are the prominent geomorphological features of this area. The dry river valley lies within longitude 102°37′–103°58′ E and latitude 30°50′–33°10′ N, and stretches over 150 km through five counties along the upper reaches of the Minjiang River. Much of this area was covered by forests 600-700 years ago (Shi and Yong 2001; Fang and Zhang 2002; Sun et al. 2005; Ye et al. 2002). Repeated disturbances in the distant past and destructive exploitation of the forest resources in more recent times have degraded a large part of this area (Li 1990; Bao and Wang 2000; Fan and Zhang 2002; Ye et al. 2002). Now an arid climate and easily erodible soils on steep and often unstable slopes form a vulnerable arid and semi-arid dry river valley ecosystem covering a total area of more than 150 000 ha (*cf.* Li et al. 2006). The degraded ecosystem has long passed the threshold of irreversibility in terms of its structure and function (*cf.* Aronson et al. 1993; Liu et al. 2001; Liu et al. 2003). Native vegetation is limited in coverage and diversity, and is dominated by arid shrub communities (Ye et al. 2005; Ye et al. 2006). Native tree species are difficult to re-establish on the degrade slopes (Winkler 1996; Mykrä and Salo 2000; Bi et al. 2003; Liu et al. 2001; Zheng et al. 2005). Soil erosion, landslides and debris flows threaten the livelihood of the already impoverished surrounding communities, damage roads and bridges and often block traffic for hours, even days, in the more severe cases (Xie et al. 2004; He et al. 2005). The sediment delivery, between 1000 to 5000 t $km^{-2} \cdot a^{-1}$, from this area poses a problem to the new 156 metre-high Zipingpu hydro-electric dam at the lower end of the dry river valley and the Three Gorges Dam further down stream (Lu et al. 2003; Fan et al. 2006).

The dry river valley has a warm temperate climate with a reduced influence of monsoons due to its enclosed landform. Huge variations in microclimate exist in this area because of the range of elevation and diversity of topography. The arid and semi-arid environment that characterises the dry river valley is largely confined to areas with elevation below 2000 m, where the mean annual rainfall is about 500 mm, and the mean annual evapotranspiration is greater than 1 500 mm. About 80% of the annual rainfall falls during the summer months between May and October. The mean annual temperature ranges from 8.5ºC to 13.5°C. The maximum daily temperature is 32ºC and the minimum is about -12°C. The steep slopes along the valley, usually greater than 20°, are mostly covered by loose and shallow podzolic soils, with sedimentary rocks clearly visible in places. Over the entire course of the dry river valley, extreme minimum temperatures and soil moisture supply seem to be the limiting climatic factors for *P. radiata* (Yan et al. 2006).

The areas surrounding the dry river valley in Aba prefecture are mainly covered by alpine and subalpine fir and spruce forests (Li 1990). Also growing in this region are two native *Pinus* species, *P. tabulaeformis* and *P. armandii,* which can be found in both native forests and plantations (e.g. Lei et al. 2004, Sun et al. 2005). *P. tabulaeformis* is a two needle pine which has a wide distribution in cold temperate and some low rainfall regions from northern to central China and northern Sichuan. It grows from 0–2 600 m above sea level and can form extensive forests in parts of China (*cf.* Ni et al. 2001; Zeng et al. 2005). *P. armandii* is a five needle pine with a wide and discontinuous distribution in China. It occurs in 12 provinces in central and southwest China with latitude ranging from 23°30’ to 36°30’ N and longitude from 85°30′ to 113°00′ E, and grows mainly in the mountainous conifer forests with elevation ranging between 1000-3000 m (Ni et al. 2001; Wang and Hong 2004). It is often found with deciduous broadleaf species such as *Betula luminifera*, *B. utilis var. sinensis* and *Quercus longispica* in mixed forests. The two native pines are among the major species of the temperate coniferous forests in China (Wu 1980).

Scope and Methods of Assessment

Since *P. radiata* is an extensively planted conifer species in the world, there has been a vast volume of literature on its pests and diseases (e.g. Chou 1991; Lewis and Ferguson 1993; Lavery and Mead 1998; Wingfield et al. 2001). Literature is also abundant on the indigenous forest tree pathogens and insect pests in China (e.g. Cai et al. 1983; Mao 1998; 2000; Shao and Xiang 1997; Xiao 1992). This paper does not aim to evaluate the risks posed by all indigenous and exotic pathogens and pests in the literature to the introduced *P. radiata* in the study area. It concentrates on those that are considered to be potential causal agents of serious forest health problems for the introduced species.

By reviewing the forest health literature on *P. radiata* and on *Pinus* species in China, we identify both the indigenous and exotic pathogens and pests that pose a potential threat to the long term success of *P. radiata* introduction in the study area. In doing so, the full text of scientific papers, published and unpublished reports from various sources was read to extract relevant information. Historical records of pest and disease outbreaks in the coniferous forests of Aba prefecture and that of past forest health surveys in the area were examined in relation to the objectives of this survey and assessment. Some specific information was also gathered from personal communications with other forest health experts. This broad forest health literature and information review provided a comprehensive understanding of the global and local forest health environment for the introduced *P. radiata* and served as a starting basis for the assessment of forest health risks to the long term success of the introduction.

In addition to the broad literature and information review, field surveys and inspections have been conducted over the last four years to further identify potential damaging agents and provide information for the assessment of forest health risks. The first survey and field inspection was conducted by Chinese forest entomologists and pathologists in 2002. A following survey was conducted two years later by a joint team of Australian and Chinese forest entomologists and pathologists in the summer season of northern hemisphere when pests and diseases start occurring in the forests. This survey and inspection covered the complete age range of plantings within the area. The youngest was new plantings established a year earlier and the oldest was a small

area planted about 13 years ago. Apart from this oldest patch, all other plantings were under 8 years old and the trees were mostly less than 5 m in height. Since the plantations were planted in widely separated small patches on the steep and often unstable slopes, they gave a complete view of the stand and canopy conditions from a distance. Ten representative planting sites were selected for field survey and inspection.

At each site a broad visual inspection of the general stand conditions such as stand density, growth vigour and signs of drought stress was carried out first by walking through the planting area to assess its potential vulnerability to pest and pathogen attacks and also to spot patches possibly with forest health problems. The presence of diseases and insect pests was noted and their level of infestation was recorded as high or low. Then a representative stand was located within the spotted patch for more detailed assessment. Foliage, branch, bark and root samples and insect specimens were collected during the field survey and inspection. Some pathogens and insect specimens were identified in the forest pathology and entomology laboratories in China; other specimens were taken to Australia for further identification and examination. In addition, some silvicultural practices that inadvertently affected forest health were noted. Selected stands in the native coniferous forests adjacent to the dry river valley area were also inspected to sample possible causal agents to the introduced *P. radiata*. Following this field survey and inspection, the planting sites have been monitored at least twice a year over 2005 and 2006 using a combination of transect method and examination of selected representative stands. Where a particular pest was found to cause a forest health problem, the incidence, extent and severity of symptoms have been recorded. The survey methods and preliminary results were reported in Ou et al. (2005), Zhou et al. (2005) and Xiao et al. (2006).

The forest health information from the comprehensive review, field surveys and inspections in 2004 and subsequent forest health monitoring were evaluated and analysed to produce a list of indigenous and exotic pathogens and pests that pose a potential threat to the long term success of *P. radiata* introduction in the study area. For each pathogen and pest on the list, the likelihood of an attack and the impact of the possible attack over the foreseeable future were rated as low, moderate or high. The rating was based on the best available biological information and expert knowledge of the assessment team on stand vulnerability and the abundance of insect and pathogen, the two most important factors indicating forest health risks (Paine et al. 1984; Dymond et al. 2006). Where both the likelihood of an attack and its impact were uncertain, it was identified as a gap to be filled by future investigations. Pathological descriptions, diagnostic symptoms, major life cycle events of insect pests and their bionomic characteristics are not the emphasis of this paper.

Indigenous pests and pathogens

In 1980 a comprehensive national forest pest and disease survey was conducted in China. A number of indigenous pests and pathogens were detected on the two native pines, *P. tabulaeformis* and *P. armandii* in the areas surrounding the dry river valley. The record of this survey was updated by the more recent forest health surveys conducted since 2002. So far 13 species of insects and 10 species of fungal pathogens have been found to affect the health of the native pines including nursery seedlings. These insect species cause damage to needles, buds, shoots, stems and cones (Table 1), and the pathogens cause needle blight, needle cast, needle and stem rust, canker and molds (Table 2).

Table 1. Main species of insects on the native pine species in Aba Prefecture, Sichuan Province, China

Pest category	Insect species	Host species
Needle feeders	*Acantholyda posticalis*	*P. tabulaeformis, P. armandii*
	Lymantria dispa asiatica	*P. tabulaeformis, P. armandii*
	Neodiprion sp.	*P. tabulaeformis*
Bud/shoot feeders	*Blastophagus* sp.	*P. tabulaeformis, P. armandii*
	Rhyacionia sp.	*P. armandii*
	Dioryctria splendidella	*P. tabulaeformis*
Stem borers	*Ips sexdentatus*	*P. tabulaeformis*
	Polygraphus sinensis	*P. tabulaeformis*
Sap suckers	*Aieyrodidae* sp.	*P. armandii*
	Cinara sp.	*P. tabulaeformis*
Cone eaters	*Dioryctria* sp.	*P. tabulaeformis*
Nursery seedlings	*Polyphylla* sp.	*P. tabulaeformis, P. armandii*
	Agrotis sp.	*P. tabulaeformis, P. armandii*

Table 2. Main species of pathogens on the native pine species in Aba Prefecture, Sichuan Province, China

Disease category	Pathogen species	Host species
Needle diseases	*Pestalotiopsis* sp.	*P. tabulaeformis, P. armandii*
	Lophodermium sp.	*P. tabulaeformis, P. armandii*
	Coleosporium sp.	*P. tabulaeformis, P. armandii*
	Capnodium sp.	*P. armandii*
Stem and branch disease	*Cronartium ribicola*	*P. armandii*
	Cronartium flaccidum	*P. tabulaeformis*
	Cronartium orientale	*P. tabulaeformis*
	Cytospora sp.	*P. armandii*
	Phomopsis sp.	*P. armandii*
	Cronartium quercuum	*P. tabulaeformis*
	Sphaeropsis sapinea	*P. tabulaeformis*
Nursery seedlings	*Fusarium* sp.	*P. tabulaeformis*
	Rhizoctonia sp.	*P. tabulaeformis*

Although *P. radiata* has been cultivated in Sichuan for only a relatively short time in widely separated small plantations, some of the indigenous pest and pathogen species in Table 1 and 2 have already been detected on *P. radiata* in forest health surveys conducted since 2002 (Table 3 and 4). In addition, three pathogens, *Pestalotiopsis* sp., *Fusarium* sp. and *Rhizoctonia* sp., have been found to infect *P. radiata* seedlings at the nursery. No root or butt disease, vascular wilts, cankers or stem disease have been observed. These indigenous pests and pathogens may become more adapted to the exotic pine over time and so will represent an increasing pest and disease load to the introduced *P. radiata*.

Table 3. Pests found on *P. radiata* and their level of infestation

Pest category	Insect species	Level of infestation
Needle feeders	*Acantholyda posticalis*	High at Xiaomiaoshan, low at all other sites
	Neodiprion sp.	High at the provenance trial site in Wenchuan, not present at other sites.
	Lymantria dispar	Low, present at all plantation sites
Bud/shoot feeders	*Dioryctria rubella*	Low, present at all plantation sites

Table 4. Pathogens found on *P. radiata* and their level of infestation

Disease category	Pathogen species	Level of infestation
Needle disease	*Pestalotiopsis funerea*	Present in all plantations, high at the plantation site in Li Xian, low at other sites
	Lophodermium spp.	Low, present in plantations
Shoot disease	*Sphaeropsis sapinea*	Present in plantations at Wenchuan and Mao Xian.

Specific forest health risks posed by indigenous pests

Acantholyda posticalis Matsumura (pine web-spinning sawfly)

This species is relatively widespread in parts of northeast and central China causing damage to native pine trees (Xiao 1992). Its native hosts in Aba prefecture are *P. tabulaeformis* and *P. armandii*. During the field survey and inspections in 2004, it was found on *P. radiata* in plantations older than 10 years at two sites within Mao Xian County. The infestation caused severe defoliation to some 13-year-old *P. radiata* trees at the poorer site under severe drought stress. Most trees at this site seemed to lack growth vigour and the stand had not reached full canopy closure after 13 years. However, infestation levels were lower and damage seemed less severe on the native pines planted in the same area, and on *P. radiata* at better sites.

Subsequent observations revealed that *A. posticalis* is univoltine in this area. Adult insects emerge and lay eggs in the elongating shoots in early to mid May in this area. Hatching takes 15–17 days and the young larvae start to feed on the needles in June. They usually spin out 3–5 fine hairs to weave a net at the base of pine needles, and then bite off the top half of the needle to feed in the net. The third instar larvae migrate to the base of the new shoots where they weave a much solid nest to feed inside. Feeding peaks at the fourth instar during which each larva can consume 2.5 g of needles. The larvae start to migrate to the forest floor in late June. By mid July, the mature larvae retires into the forest floor and subsequently spends the winter in the soil as a prepupa.

No natural parasites of the eggs or larvae of *A. posticalis* have been found in this area so far, although they have been recorded in other parts of China (Xiao 1992). The adult insects can spread easily. However, methods for forecasting infestation levels, protective treatments and chemical control are available from the Chinese forest health literature (e.g. Lou et al. 1990; Guan 2004; Wang et al. 2004; Wu 2005). Biological control using *Trichogramma dendrolimi* Mutsumura and *Encyrtusb* sp. has been experimented in Fushu, northeast China, but was not successful (Chen et al. 2005). Although the likelihood of an attack posed by this pest is high, the impact of attack is considered only to be medium since preventative and control measures can be taken before and after the detection of an outbreak.

Nesodiprion sp. (pine sawfly)

This pine sawfly has not been previously detected in the dry river valley area and its occurrence has not been reported in other areas of Sichuan province. The species has yet to be identified. Although larva specimen is sufficient to identify two *Desodiprion* species (Xu 1998), the identification of this particular species rely on the collection of both larva and adult insect specimens. During the field survey and inspections in 2004, larvae were found in isolation on the outer foliage of *P. radiata* in the plantation at Li Xian County. In the summer of 2005, a localised outbreak caused defoliation to some of the 1-year old trees at the *P. radiata* provenance experiment site at the lower stretch of the dry river valley. Some trees were so severely defoliated that they did not put on enough growth to survive through the following winter. Infestation of this sawfly was also detected in *P. radiata* plantations in Mao Xian, causing some defoliation to the established trees. Subsequent monitoring revealed that outbreak tends to take place from late July to early August. Protective treatments and chemical control were applied to prevent any further infestation and damage at the experimental site in 2006.

Several species of the genus, *Nesodiprion,* have been reported in the literature in China, including *N. huanglongshanicus, N. zhejiangensis, N. deqenicus* and *N. biremis* (Yu 1998; Liu et al. 1994; Xu 1998; Xu et al. 2001; Jiang et al. 1993). *N. huanglongshanicus* is bivoltine in the northern province of Shandong. It was reported to damage *P. tabulaeformis* and *P. armandii* in areas around Huanglong mountain in Shanxi Province, and *Cedrus deodara* in mountain Taishan of Shandong Province (Liu et al. 1994). *N. zhejiangensis* has a wide distribution from central to southern China, and its host includes the native *P. massoniana* and the introduced *P. teada, P. elliotii* and *P. thunbergii* (Jiang et al. 1993; Xu 1998). *N. deqenicus* and *N. biremis* have a much narrower distribution, being found mostly in Yunnan Province where they cause damage to *P. yunnanensis*, *P. densata* and *P. kesiya* var. *langbianensis*.

Although the likelihood of an attack posed by this pest is particularly high, the impact of attack is considered only to be medium since *P. radiata* has been planted in widely separated small plantations and control measures can be taken before and after the detection of an outbreak. Some chemical and biological control methods for the *Nesodiprion* species have been well documented in Yu (1998) and Xu et al. (2001).

Lymantria dispar asiatica (Asian Gypsy moth)

The Asian gypsy moth *Lymantria dispar asiatica* Vnukovskij is recently recognised as one of the two subspecies of *Lymantria dispar* (Pogue and Schaefer 2007). In China its distribution is mainly within latitude 20° to 58° north, covering about 20 provinces (Xiao 1992; Wang et al. 2006). This extensive distribution is partly attributed to its extremely wide host range, more than 500 plant species in China (Xiao 1992). Being a polyphagus defoliator, it can cause damage to many trees of both coniferous and broadleaf species. Consequently, there is a substantial amount of literature in China on the biology (e.g. Lin et al. 2000; Wang 2001), ecology (Sun et al. 2001; Shi et al. 2004) and physiology of the gypsy moth (e.g. Liu et al. 2004; Wang et al. 2006). The life cycle, bionomics and population dynamics of the gypsy moth appear to be well understood where it has become a forest health problem. The level of infestation and the extent of damage caused by the gypsy month to forest trees have been found to be associated with canopy density and site quality. For-

ests in small patches with low canopy cover on poor sites tend to be the most severely affected (Shi et al. 2004). To prevent outbreaks of the gypsy moth and to reduce its damage, integrated management practices have been widely adopted in China (e.g. Li 2001; Zhang et al. 2001), where bioinsectcides play a prominent role (Hu 2002; Zhang et al. 2005). In addition, many natural enemies of the gypsy moth have been found in China, including 91 species of insects, comprising 55 parasitoids and 36 predators, fungi, bacteria and viruses (Schaefer et al. 1984; Yan et al. 1994a; b; Li et al. 2001; Hu 2002). These natural enemies can result in substantial natural mortalities of *L. dispar asiatica*. Field studies conducted in Dayi County, Sichuan Province showed that about 88% of the gypsy moth individuals were killed by natural enemies from egg to pupal stage (Yan et al. 1994a). These natural enemies can help suppress and prevent gypsy moth outbreaks through natural regulation in many places in China (Yan et al. 1994a; Hu 2002).

Gypsy moth outbreaks have caused damage to *P. massoniana* and other broadleaf species in areas around Chengdu in the Sichuan basin (Chen 1988). No such outbreaks have been observed or reported in the *P. tabulaeformis* and *P. armandii* forests within the province. Although the gypsy moth has defoliated forests of the two pine species in other provinces (Lan and Wan 2000; Li 2001), they are not the preferred host species and the larvae cannot complete development on their needles (Shi et al. 2004). *L. dispar asiatica* is univoltine in the natural forests of *P. massoniana* of Sichuan (Chen 1988). Female moth lay eggs in masses, each having 400–1200 eggs. During an outbreak, more than 100 egg masses on average can be found on each tree. Larvae develop through five instars over a three month period from March to May each year before pupating for about 2 weeks. Adult insects emerge between late May and early June, surviving for about a week or so while laying eggs. Fully formed larvae over-winter in eggs undergoing obligatory diapause.

The gypsy moth has a distribution throughout the dry river valley area. It was present in all *P. radiata*, *P. tabulaeformis* and *P. armandii* stands as detected by forest health surveys and field inspections conducted since 2002. The gypsy moth was present on between 10% and 15% of the trees with an average of 1.2 individuals per tree in *P. radiata* plantations. This population density was too low to cause any forest health problems at present. However, the population dynamics of gypsy moth follows a typical cyclical pattern where population density goes through the rise, peak and fall of one population cycle over a period of 8-9 years (Sun et al. 2001; Wylie et al. 2006). The population density of gypsy moth in the *P. radiata* plantations may be at the lower end of oscillation at present. If so, it is likely to increase over the next few years and large eruptive populations in the future can not be ruled out at this stage. It has been reported that *P. radiata* forests were damaged during outbreaks of *L. dispar dispar*, the European subspecies, in Spain and Moroco, particularly when the preferred food sources from broadleaf species were exhausted (Romanyk 1973; Rabasse and Babault 1975; Fraval 1989). Another reason for the low population density is that *P. radiata* may not be a preferred host of *L. dispar asiatica*. In comparison with species of the preferred host genera, *P. radiata* is considered to be a resistant species to the gypsy moth (Liebhold et al. 1995). Although the gypsy moth can feed as newly hatched larva, and complete development, on the foliage of *P. radiata* (Matsuki et al. 2001; Withers and Keena 2001), it is regarded as posing a low to moderate threat to *P. radiata* in New Zealand, should it ever establish there (Withers and Keena 2001)

The likelihood of an attack posed by this pest is considered to be medium and the impact of attack is considered to be low for *P. radiata* plantations in the study area. However, the impact is likely to become more severe once it has run out of preferred hot foliage. Results of the on-going forest heath monitoring of these plantations will be of particular interest to Australia since this pest has been recognised as a potential threat to *P. radiata* and native species plantations in Australia and a response plan and strategy for it incursion is being prepared (Wylie et al. 2006).

As stands of *P. radiata* establish it is likely that species of *Quercus* and other preferred hosts of *L. dispar asiatica* will establish as an understorey. When the communities of plants in the *P. radiata* plantations become more diverse the impact of Asian gypsy moth may be greater. It should also be noted that there are numerous other species of *Lymantria* in China (Schintlmeister 2004), as well as many other Lepidoptera, the larval stages of which feed on *Pinus* foliage (Cai et al. 1983; Xiao 1992). It would be surprising if some of these insects did not adapt to feeding on *P. radiata*. Some molecular studies of genetic diversity and phylogenetic relationships of species of *Lymantria* in Sichuan and China would be of considerable scientific and practical use. Species to be examined include in subgenus *Porthetria*: *L. apicebrunnea* Gaede, *L. dispar dispar, L. schaeferi* Schintlmeister, and in subgenus *Lymantria*: *L. concolor septentrionalis* Schintlmeister, *L. monachal* and *L. similis similis* Moore.

Dioryctria rubella Herrich-Schaeffer (Pine tip moth)

Among the pine shoot pests in China, the pyralid species of the genus *Dioryctria* Zeller are the most widely distributed and cause the most conspicuous damage to many pine species throughout the country (Wang and Song 1985; Tian and Yan 1989; Xiao 1991; Qian 1992). The pine tip moth found in the *P. radiata* plantations in Aba is *D. rubella* Hampson, which was mistaken as *D. splendidella* Herrich-Schaeffer by many authors before the revision of the classification of *Dioryctria* species in China by Wang and Song (1982; 1985). *Diocrytria rubella* is distributed throughout China and its hosts in Sichuan include all the native pine species i.e. *P. tabulaeformis*, *P. armandii* and *P. massoniana*. The number of life cycles that *D. rubella* completes per year varies with geographical location. It overwinters as larvae either in shoot tissue or in cones. During spring of the following year, it resumes feeding activity in the same shoot or move to mine a new shoot or a developing cone. Larvae mature after the 5th instars. The mature larva usually chews out a circular hole at the top of their feeding tunnel and covers it with pitch masses containing wood dust and frass to form a pupation site. Pupation takes about 15 days. Adults lay eggs along the grooves of yellowing needles on the infested shoots. The newly hatched larvae stay in the tunnel or under the bark for 3-4 days before feeding, and about half of the young larvae move to mine the

tender tissues of new shoots.

The damage caused by *D. rubella* usually results in crooked, forked and multiple leader trees as well as growth reduction and degradation of timber and seed quality (Tian and Yan 1989; Zhang et al. 1989; Xi et al. 1990; Su and Pan 2006). In the most severe cases, it can lead to mortality of young trees, but not older ones. Since the new shoots that *D. rubella* mines and feeds on need to be above certain minimum size, the level of infestation tends to be dependent on tree and stand age. Such an example was demonstrated by Zhang et al (1989) in *P. tabulaeformis* plantations. The level of infestation and damage was minimal before age 5, but it increased with stand age soon afterwards and reached a peak at age 10 before a decline thereafter. A particular study by Yang (1993) using stem analysis data showed a similar pattern of *D. rubella* infestation and damage in *P. armandii* forests. Trees in young and unthinned stands were infested more than those in older stands. The infestation tended to be more pronounced when trees were under drought stress and less vigorous. Based on the population dynamic of *D. rubella,* Xi et al. (1990) developed a sampling method to predict its population density so that control measures could be put in place in advance to prevent unacceptable infestation levels and wide-spread damage. The control measures are well documented, which include the use of chemical sprays, biological agents and silvicultural treatments such as thinning and shoot trimming (Tian and Yan 1989, Qian 1992). The likelihood of an attack posed by this pest is considered to be medium and the impact of attack is considered to be low for *P. radiata* plantations in the study area.

Aieyrodidae sp (Armand pine mealy lice)

This pest is a piercing-sucking insect that started to appear in *P. armandii* forests in an area adjacent to the dry river valley in the 1990s. It appears to be an undescribed species of *Aleyrodidae* as tentatively judged by project scientists following a preliminary examination, but the exact identification of this species is still unknown. Over the last few years this pest has become widespread in the *P. armandii* forests in Jiuzhaigou National Park, a world natural heritage area, causing sporadic tree mortality.

Female adults lay eggs on the pine needles after mating. First instar nymphs stay on the needles, and then gradually move onto one-year old shoots to search for fresh and soft tissues to pierce and suck. After the second instar, nymphs become flattened with much reduced legs and antennae before losing mobility. By excreting a sticky fluid they become sessile on the shoots, twigs and branches in the form of a dark brown scale. The attacks by these insects result in the loss of turgor and subsequently drooping and collapse of the foliage and succulent tissues on the new shoots. Such damage weakens the trees and reduces their vigor and resistance to pathogens of *Cytospora sp.* and *Phomosporsis sp.* Subsequent infections of these pathogens cause shoot blight, crown wilt and ultimately tree death in *P. armandii* forests.

The likelihood of an attack by this piercing-sucking insect and its impact on the introduced *P. radiata* are uncertain. This gap of information can only be filled by future research which is outside the scope of this assessment.

Specific forest health risks posed by indigenous pathogens

Pestalotiopsis funerea (Desm.) Steyaert (pine needle blight)

Pine needle blight is a common foliar disease of a wide range of pine species and the causal fungi are often host-specific. The fungus causing needle blight of the native pine species in Aba prefecture is *Pestalotiopsis funerea* (Huang and He 2000), which infects mostly current year needles. Its mycelium and conidia overwinter in the infected needles on the tree and seldom on the forest floor. Major spore releases and infection of new needles start from late May and last to early July when air temperature within the forests reaches 20ºC and humidity is greater than 65%. At the early stage of infection after the start of the new growing season in late May, the needles develop 1–20 circular or oblong yellow spots. It takes about 10 days for the needle tips to begin to die back, with a dying section about 0.4–0.6 cm turning yellow. In about another 10 days, the dying section turns brown and expands to about 1–3 cm. As infection progresses, the yellow spots become somewhat contracted and turn light-gray or dark gray with red brown outer rings bordering healthy tissues. Before the end of the growing season in October, small black spots of fruit bodies formed by acervuli and conidia appear on the infected areas. When heavily infected, the forest canopy appears during July and August as if scorched by fire (Huang et al. 1999).

Pestalotiopsis needle blight is more severe in *P. tabulaeformis* than in *P. armandii* forests in Aba prefecture. It is particularly widespread in three counties: Heishui, Mao Xian and Jiuzaigou, infecting more than 6 000 ha, about half of the total area of *P. tabulaeformis* forests in Aba (Huang et al. 1999). The infected forests are within an elevation range between 1 300 m and 3 100 m, and young trees between 5 and 13 years of age are the most affected. Over 90% of trees were infected in some stands, resulting in growth reduction and sporadic mortality (Huang et al. 1999; Huang and He 2000). The rate of infection and the severity tend to increase with stand density and vary with topographical positions because of their influence on the temperature, humidity, wind and air flow within the forest stands. Stands along lower slope and on more exposed aspects seem to have a higher rate of infection (Huang et al. 1999).

Our forest health survey and field inspections in 2004 and subsequent monitoring indicate that *Pestalotiopsis* needle blight is also widespread in *P. radiata* plantations. It was observed in all plantations in 2004 but the rate of infection seemed too low to cause any major damage (Xiao et al. 2006). However, needle blight has become more pronounced partly because the trees have been under much greater moisture stress after the drought in 2006 and early 2007. The latest field inspection in June 2007 of the 3-three year old provenance experiments and other plantations has found a significant increase in both the rate of infection and severity of the disease. It is one of the factors contributing to the observed mortality in the young plantings. From a distance, the oldest plantation at Xiao Gou in Mao Xian looked like as if it was scorched by fire. All 16-year-old trees had been infected with much greater severity than in 2004. The high planting density of over 3000 trees/hm^2 on a site with a mean annual rainfall

of about 500 mm has greatly exacerbated the drought stress for the trees. The needle blight will further reduce tree vigor and eventually lead to significant mortality if the plantation is not thinned in the near future.

Lophodermium conigenum (Brunaud) Hilitz and *L. pinastri* (Schrad.) Chev. *(Lophodermium* needle cast)

Pine needle casts are major diseases affecting all pine species in Sichuan and the causal fungi have been identified to be six species of *Lophodermium* (Liu et al. 2004). In Aba Prefecture, *L. conigenum* and *L. pinastri* are the species causing needle cast of *P. tabulaeformis* and *P. armandii*. They usually infect trees already weakened by *Pestalotiopsis* needle blight and seem to damage 2-year old needles more than the current year needles. The pathogens have a full life cycle a year and overwinter in the form of intercellular mycelium in living needles or apothecium in infected dead needles. Ascospores are the principal agents of infection and dispersal (Choi and Simpson 1991). At the early stage of infection, yellow spots appear on the needles. These spots enlarge and merge into transverse bands and the needles turn yellow or yellowish-brown. As infection progresses, dark brown spots (pycnidia) form on the yellowish brown bands. In late spring and early summer, pycniospores are formed that are spread with wind in rainy days or during moist periods (Gao and Wang 2004). When heavily infected, the forest canopy appears as if scorched by fire before needle shedding. The dark transverse bands on the fallen needles' may be formed together with apothecia. The ripe apothecium is elliptic with a longitudinal slit through the middle.

The presence of *Lophodermium* needle cast in the dry river valley area was first detected during the comprehensive pest and disease survey in 1980. It has already occurred in some *P. radiata* plantations, although as a secondary infection following *Pestalotiopsis* needle blight. However, the relatively low rainfall in the dry river valley area is unfavourable to development of epiphytotics of needle cast pathogens such as species of *Mycosphaerella* and their anamorphs, or to members of Rhytismataceae including species of *Lophodermium* or *Cyclaneusma* (Ades and Simpson 1991; Choi and Simpson 1991). The likelihood of *Lophodermium* needle cast infection is high, but its impact on *P. radiata* may only be secondary to *Pestalotiopsis* needle blight.

Coleosporium spp. (Pine needle rust)

The pathogens of pine needle rust belong to *Coleosporium*, a genus of numerous described species. All species are biotrophic and most are heteroecious with complex life cycles (Harrington and Wingfield 1998). The symptoms of pine needle rust caused by the different pathogens are similar and well described in the literature. There are 48 species of *Coleosporium* that are known to cause pine needle rust in China and (Pan and Xue 1991). All but one are macrocyclic. In Sichuan, *C. solidaginie* has been identified to infect *P. armandii*, with *Solidago spp.* being the alternate hosts (Pan and Xue 1991). *Pinus tabulaeformis* is also susceptible to infection by species of *Coleosporium* in China (Pan and Xue 1991; Ge 1989). The Sichuan species of *Coleosporium* mostly infect young stands of *P. armandii* and *P. tabulaeformis* in the mountainous region in the west of the province (Chen 1989). In the dry river valley area, needle rust has been observed on *P. tabulaeformis* in Mao Xian and Li Xian, although no significant damage occurred.

So far no needle rust has been detected on *P. radiata* since its introduction to Aba 15 years ago. *P. radiata* trees in California are known to be sometimes infected with species of *Coleosporium* pacificum Cummins (Farr et al. 1989). Pathogenicity tests in the laboratory would be desirable to establish the susceptibility of *P. radiata* to the species of *Coleosporium* known from Sichuan. There is a likelihood that needle rust will occur on the introduced *P. radiata* when environmental conditions are suitable and alternative hosts are present.

Cronartium flaccidum (Alb. & Schwein.) G Winter (Resin top disease); *C. orientale* S. Kaneko (Asian gall rust); *C. quercuum* (Berk.) Miyabe (Gall rust); *C. ribicola* Fischer (white pine blister rust)

Stem rusts are caused by pathogens that reside in the stem rust genera *Cronartium, Endocronartium* and *Peridermium* (Harrington and Wingfield 1998). The pathogen causing pine blister rust is *C. ribicola* in southwest China, where the alternate hosts include *Ribes* species or *Pedicularis* species (Yang et al. 2003; Hu 2004). The disease has caused significant damage to even-aged *P. armandii* plantations (Ma et al. 1999; Yang et al. 2003; Zhou et al. 2006). In Sichuan province, it occurs mainly in the mountainous regions around the Sichuan basin. In the early 1990s, more than 15 000 ha of forests were infected, representing about 13% of the total forest area of *P. armandii* in the province (Yang et al. 1997). In Aba Prefecture, pine blister rust was present in three counties, among which Mao Xian and Wen Chuan are in the dry river valley area where *P. radiata* has been planted. It infected about 6 000 ha of *P. armandii* forests in the Prefecture. In the severest cases, mortality caused by the blister rust was so extensive that the whole forest stand could be killed off.

The disease is usually first detected by a slight swelling around the base of the infected branches off the lower stem of *P. armandii*. The infection usually damages the bark rather than the xylem. Sometimes the swelling occurs on both the stem and branches simultaneously. Cracks start to appear in the swollen area usually in May and from within the cracks light yellow vesicles are produced. The vesicles become orange colored and broken usually in June when aeciospores are released and spread by wind. By the end of June, most aeciospores are released and the infected area appears rather rough and is often covered by sooty moulds due to secondary infection by *Capnodium* species. In September, milky white dews with pycniospores appear on the top and sometimes bottom margins of the infected areas. Later the dews become orange colored and sweet. When debarked and dried, the infected area is dark red, resembling a blood stain (Yang et al. 1996). *Cronartium ribicola* is not known to infect hard pines so *P. radiata* will not be susceptible.

Two other species of *Cronartium* are known to occur in Sichuan on hard pines: *C. flaccidum* (with microcyclic form *Peridermium pini*) and *C. orientale* S. Kaneko (Teng 1996;

Zhuang 2005). *Cronartium orientale* was formerly known as *Cronartium quercuum auct.* and is the Asian sister taxon of that species (Kaneko 2000). The alternate hosts for *C. flaccidum* are species of Scrophulariaceae (Zhuang 2005) and for *C. orientale* species of Fagaceae (Kaneko 2000). Species of Quercus are widespread in native forests in Sichan though not common in areas being planted with *P. radiata* (Li 1990).

So far no stem rust has been found on *P. radiata* in the study area. Perhaps the relatively low rainfall in the dry river valley area and the lack of alternate hosts are unfavourable to the infection by and development of spore forming structures. *Pinus radiata* trees in California are known also to be sometimes infected with *Cronartium coleosporioides* Arthur, *C. quercuum* (Berk.) Miyabe ex Shirai and the autoecious *Endocronartium harknessii* (J. P. Moore) Y. Hiratsuka (Farr et al. 1989). Therefore there is a probability that stem rust infections will eventually occur on *P. radiata* in Sichuan. If so, the impact will most likely be high.

Exotic pests and pathogens

In its native environment, *P. radiata* is affected by a number of pathogens. Some are innocuous, while others cause serious damage. The needle blight pathogen, *Dothistroma septosporum* (Dorog) Morelet, is among the former, but its prevalence on other pines in North America has increased over the past decade (Bradshaw 2004; Woods et al. 2005). Another example is *Melampsora larci-populina*, causing larch-popular leaf rust that was found on *P. radiata* in California (Newcombe and Chastagner 1993; Newcombe et al. 1994). Other pathogens causing more serious damage include dwarf mistletoes, two gall rusts, two root diseases and pitch canker (McDonald and Maacke 1990; Gordon et al. 2001; Wikler et al. 2003; Wingfield et al. 2006). The dwarf mistletoe (*Arceuthobium occidentale* Engelmann) infects trees of all ages. One species of *Arceuthobium*, *A. pini* Hawksworth and Wiens, occurs on *P. tabulaeformis* in China, but it is not known whether *P. radiata* is susceptible (Hawksworth and Wiens 1996). Western gall rust (*Peridermium harknessii* J.P. Moore) and coastal gall rust (*Peridermium cerebroides* Meinecke) can cause significant damage to young trees. Although the pathogen has not been recorded in New Zealand, it has been recognised as a serious potential threat to *P. radiata* plantations in the country (Ramsfield et al. 2007). *Pinus radiata* trees in California are known also to be sometimes infected with *Sphaeropsis sapinea* and species of *Coleosporium* and *Cronartium* (Gadgil and Bain 1999). All three of these genera occur in Sichuan. The two root disease pathogens are species of *Heterobasidion* and *Armillaria*. Both genera occur in China. Since the 1980s, pine pitch canker caused by *Fusarium circinatum* has become a serious disease of *P. radiata* in California (Gordon et al. 2001; Storer et al. 2002). The disease is restricted to the foggy coastal regions in California and is more severe closer to the coast. This pathogen is now also well established in all three mainland native populations of *P. radiata* where it causes conspicuous branch die-back, and frequently in association with native bark beetles, increased tree mortality (Wikler et al. 2003). The disease now poses a serious threat to the diminishing indigenous populations of *P. radiata* (Bohne and Rios 2005). *Fusarium circinatum* is a pathogen of quarantine concern that could be introduced to China on infected pine seed (Gadgil et al. 2003).). In Australia and New Zealand *Cyclaneusma minus* (Butin) DiCosmo, Peredo & Minter is a pathogen of *P. radiata* of major economic significance (Choi and Simpson 1991). This pathogen is known from *P. tabulaeformis* and *P. banksiana* in northwestern China (Zhuang 2005) and was possibly introduced with germ plasm of the latter host. *Cyclaneusma minus* has not been observed on *P. radiata* in Sichuan.

Although many insects feed on the needles, twigs, branches and stems of *P. radiata* within its natural range, only few of these cause significant damage. They include four bark beetles (*Ips mexicanus* (Hopkins), *I. plastographus* LeConte, *I. confusus* (LeConte), *Dendroctonus valens* LeConte) and a weevil (*Pissodes radiatae* Hopkins); all are cambium feeders (McDonald and Maacke 1990). *D. valens* was detected in pine forests in China in 1999 and has spread to four provinces (Hebei, Henan, Shaanxi and Shanxi) infesting over half a million hectare of forest and killing more than 6 million *P. tabulaeformis* trees (Li et al. 2001; Yan et al. 2005). The outbreak is continuing and still spreading (Yan et al. 2005). The pest is thought to have been introduced to China in unprocessed logs imported from the west coast of the U.S.A. in the 1980's (Yan et al. 2005). *D. valens* is a widespread pest of pines in North America, but is generally regarded as a secondary pest (Smith 1971; Britton and Sun 2002). However, it is likely a vector of *F. circinatum* because of its association with the pitch canker disease in California (Storer et al. 2002). In China several consecutive years of drought are thought to have favoured the outbreak of *D. valens* (Li et al. 2001). In California *P. radiata* is the species most frequently killed by *D. valens* (Smith 1971). Several species of *Ophiostoma* and their anamorphs are vectored by *D. valens* and some of which are pathogenic to pines (Klepzig et al. 1991). Should *D. valens* spread to Aba prefecture, its management will be a high priority in the *P. radiata* forests since they will be very vulnerable under moisture stress. Other insects causing minor damage in California include aphids, borers, caterpillars, moths and a pine cone beetle, *Conophthorus radiatae* Hopkins (McDonald and Maacke 1990). The most recent scientific expedition to the native *P. radiata* populations on the two Mexican Islands has found some damages by cone beetles on Guadalupe Island and also spittle bug (*Aphrophora canadensis* Walley, Homoptera: Cercopidae) on Cedros Island (Rogers et al. 2006). The beetles and the spittle bug have been associated with the development of pitch canker disease in California (Storer et al. 1995; Storer et al. 2002).

Outside its native range, *P. radiata* plantations are affected by fungal infections that cause mostly needle and stem diseases, sapstains and root rots. Lewis and Ferguson (1993) listed the more serious diseases that can significantly reduce growth and cause mortality in stands in the four major *P. radiata* growing countries in the Southern Hemisphere. Eldridge and Simpson (1987) reviewed control measures for some introduced forest diseases in Australia. The most common disease of *P. radiata* in exotic plantations and associated pathogens are given in Table 5. Among them, *Dothistroma* needle blight is considered an economically damaging disease in Australia, New Zealand, Chile

and parts of South Africa because of the severity and extensiveness of its impact (Gibson 1972; Coops et al. 2003; Stone et al. 2003, Bradshaw 2004). In New South Wales, Australia, *Sphaeropsis sapinea* is the most significant disease in *P. radiata* plantations causing widespread top death and mortality of drought stressed trees. This pathogen has already been isolated from two trees in the courtyard of Aba Forest Research Institute. Although not yet causing serious damage, pine pitch canker has now been reported from all major *P. radiata* growing regions except Australia and New Zealand (Gadgil et al. 2003), and the first outbreak of pine pitch canker in *P. radiata* plantations in South Africa has been recently confirmed (Coutinho et al. 2007).

Table 5. The most common diseases of P. radiata and pathogens in ex situ plantations

Disease	Pathogen
Needle blight	*Mycosphaerella pini* E. *Rostrup apud* Munk and its anamorph *Dothistroma septosporum* *M. dearnessii* Barr, *M. gibsonii* Evans
Needle cast	*Cyclaneusma minus (*Butin*)* DiCosmo*,* Peredo & Minter *Lophoderium* spp.
Stem disease (dieback or shoot blight)	*Sphaeropsis sapinea* *Amylostereum areolatum*
Sapstains	*Ceratocystis* spp. and anamorphs. *Ophiostoma* spp. and anamorphs.
Root rots	*Armillaria novae-zelandiae* (G. Stev.) Herink *Armillaria limonea* Stevenson *Rigidoporus vinctus* (Berk.) Ryvarden *Phytophthora cinnamomi* Rands *Phytophthora cryptogea* Pethybridge and Lafferty

The root pathogen genera, *Armillaria* and *Heterobasidion*, are widely distributed, with species having restricted geographic distributions and host ranges. One species of *Heterobasidion* (*H. parviporum*) is known from China (Dai 2005), but there is no information on their pathogenicity to *P. radiata*. *Armillaria mellea* occurs in California and it is also among eight *Armillaria* species identified so far in China (Jacobs et al. 1994; Mohammed et al. 1994; Zhao et al. 2005; Qin et al. 2007). Being sensitive to low soil moisture potentials (Whiting and Rizzo 1999), *Armillaria* species are unlikely to be a serious pathogen in pine plantations in the dry river valley area. The pathogenicity to *P. radiata* of the other species of *Armillaria* in China has yet to be determined. *Rigidoporus vinctus*is is known from China (Núñez and Ryvarden 2001) and may become a problem.

Pine wilt nematode, *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle is killing large numbers of *Pinus* trees in East Asia (Wingfield 1987) and was first detected in China in 1983 (Yin et al. 1988). It is thought this nematode has been introduced from North America perhaps via Japan. *Bursaphelenchus xylophilus* has been recorded killing pine trees in Anhui, Guangdong, Hong Kong, Jiangxi, Shandong provinces in China. The nematode has been isolated from 49 host species in China plus and another 21 by host inoculation (Song 2001). The nematode is vectored by species of *Monochamus* (Coleoptera: Cerambycidae) (Linit 1988) and species of this genus are known to occur in Sichuan. *Pinus radiata* is considered as relatively resistance to *B. xylophilus* (Bain and Hosking 1988), but is now known to be susceptible to a Chinese species, *B. hunanensis* Yin, Fang & Tarjan (Yin et al. 1988), detected in 2000 in dying *Pinus* trees in Melbourne, Australia.

Insects can also cause significant damage to *P. radiata* plantations outside of its native range. In the Southern Hemisphere, a major pest is sirex wood wasp (*Sirex noctilio* F.) which, with its symbiotic fungus *Amylostereum areolatum* (Fr.) Boidin, can cause widespread mortality in stands of any age (Madden 1988). In 1987 *P. radiata* plantations in South Australia and Western Victoria experienced more than 10% tree mortality with over 1.75 million trees killed (Haugen and Underdown 1990). The management program largely consists of annual releases of biological control agents, continuing forest health surveillance and improved silvicultural regimes (Eldridge and Simpson 1987). Sirex nematode, *Beddingia siricidicola* Bedding, has provided the most effective control in New South Wales since sirex was first detected in this state of Australia 25 years ago (Carnegie et al. 2005). Twelve species of Siricid wasps, though not *S. noctilio,* occur in China (Xiao and Wu 1983), but none is considered to be a pest of national significance. *Sirex rufiabdominis* Xiao & Wu is a significant pest of *P. massoniana* in Zhejiang. *Sirex noctilio* is endemic to regions to the north of China including Siberia and Mongolia (Spradbery and Kirk 1978), and research using climate matching has predicted it to be able to establish in China (Carnegie et al. 2006). The arrival of California pine aphid, *Essigella california* Essig in Australia in 1998 and its apparent rapid dispersal across the country since then have been causing significant concern (Carver and Kent 2000). Between 1998 and 2001, its infestation in the Green Triangle region in the south-east South Australia and south-west Victoria caused an estimated growth reduction of 230,000 m^3, valued at $6.9 million, in the mid-rotation *P. radiata* plantations (May and Carlyle 2003).

Shoot borers (*Phyacionia buoliana* (Schiff)) are more of a problem in Chile (Lewis and Ferguson 1993), where several other species of indigenous pests including *Ormiscodes cinnamomea*, a large Saturniid defoliator, are now also associated with the exotic *P. radiata* plantations (Ciesla 1997). Pine woolly aphids (*Pineus pini* L.) can reduce growth rate and cause progressive suppression of infested trees (Simpson et al. 1990a; b). It is not known if *P. radiata* is susceptible to Japanese pine needle scale, *Hemiberlesia pitysophila* Takegi or fall budworm, *Hyphantria cunea* (Drury) both of which have established in China and become damaging pests (Britton and Sun 2002).

Wood borers and bark beetles that present a risk to the health of *P. radiata* plantations in Australia, New Zealand and South Africa are *Hylastes ater* (Raykull), *H. angustatus* (Herbst), *Hylurgus ligniperda* (FABR.), *Ips grandicollis* (Eichhoff) and to a lesser extent *Arhopalus tristis* (Lewis and Ferguson 1993, Chapman 1999; Brockerhoff et al. 2006). Among these beetles, *A. tristis* attacks suppressed, damaged, or burnt trees, standing dead trees, and also logs and stumps (Suckling et al. 2001). Two examples of moth causing damage to plantations are the pine tree emperor moth (*Nudaurelia cytherea* subspp. cytherea) in South Africa and the European pine shoot moth (*Phyacionia buoliana*) in Argentina (Lewis and Ferguson 1993; Lavery and Mead 1998). In New Zealand, caterpillars feeding on needles can cause defo-

liation (White 1974; Chapman 1999), and in Australia significant defoliation has resulted from isolated outbreaks of native looper caterpillars (Lepidoptera: Geometiclae).

Silvicultural practices that inadvertently affecting forest health

Silviculture is a valuable tool in maintaining forest health since a major objective of silvicultural practices is to ensure productivity by improving stand hygiene and the growth vigor of trees (Waring and O'Hara 2005). Appropriate silvicultural practices can help prevent and mitigate forest health problems in plantations by reducing their vulnerability to attacks by insects and pathogens, while inappropriate practices may increase forest health risks (Tian and Yan 1989, Qian 1992, Gadgil and Bain 1999, Stone 2001, Waring and O'Hara 2005). During the course of our survey and assessment, some silvicultural practices inadvertently affecting tree health were observed. The most notable are planting practices, tending during early plantation establishment and stand density management. A widespread practice in the nurseries in Sichuan and other parts of China is to grow seedlings in thin plastic bags filled with growing medium rather than in hard plastic containers. The bags are stacked together to form seedling beds. When the seedlings are planted in the pits following site preparation, the bags often stay with the seedlings but not torn open. Although with aeration holes, the bags still restrict root growth and development. As a result, many young trees were found to have curled roots entangled together in the somewhat penetrated and stretched plastic bags when dug out. These trees were mostly stressed and hence very vulnerable to insect and pathogen attacks, and were also not stable on the steep slopes.

For the first few years after planting, the lack of effective and timely weed control during the summer has also weakened the young trees and indirectly increased the forest health risks in some areas of the dry river valley. The current initial planting density, well over 3000 tree/hm^2, is based on what is recognised as the optimal stand density for *P. tabulaeformis* (Sun et al. 2005), a much slower grower than *P. radiata*. This planting density is too high for *P. radiata* in the arid and semi-arid environment of the dry river valley. Trees growing at such a high stand density are often under moisture stress and so less tolerant of summer drought. The stress is thought to cause the browning of needle tips and drop of second year needles observed in the field and also to increase the severity and impact of needle blight and needle cast on the young trees. Thinning and post thinning fertilization will help reduce moisture stress and improve tree vigor and health of these dense stands. Yet this silvicultural option has not been adopted by forest mangers up till now.

Discussion

There has been considerable debate over the relative risks of pest or pathogen outbreaks on exotic versus indigenous tree species, especially in plantation settings (e.g. Chou 1981; 1991; Gadgil and Bain 1999; Nair 2001; Dalin and Björkman 2006). Since exotic trees are introduced without their associated specialist diseases and pests, it is reasonable to expect that they will be largely free of such specific forest health problems for quite some time (Gadgil and Bain 1999). Conversely, one might argue that exotic trees will be exposed to new diseases and pests to which they may have no resistance and to which they may therefore be extremely susceptible (Nair 2001). However, studies reviewed by Dalin and Björkman (2006) indicate that over time there is no major difference in insect abundance between native and introduced tree species. Some insects seem to perform well on introduced plants, which may lead to population outbreaks, whereas other native insects seem to be ill-adapted to use the introduced plants. In practice, it is not uncommon for newly introduced exotic trees to experience an initial period with few forest health problems, followed by a period in which indigenous pests and diseases gradually adapt to these new hosts (FAO 2001; Nair 2001). An increase over time in the number of pathogens on *P. radiata* has been observed in New Zealand (Chou 1991). Chou (1991) argued that a high incidence of damage by pests and pathogens was acceptable in *P. radiata* plantations if there was no market for thinnings or stands were routinely thinned to waste and the final crop trees were not seriously damaged. In Sichuan where the trees are being planted to stabilise landscapes significant mortality because of attack by pests or pathogens will probably not be acceptable.

It has been 16 years since the first introduction of *P. radiata* into the dry river valley area. Field observations by local foresters over this period and our survey and assessments show that indigenous pests and diseases are the main forest health concern to the introduced species at present and perhaps also in the near future. The major indigenous pests that have already adapted to the introduced *P. radiata* are the pine sawflies of *Desodiprion spp.* and *A. posticalis*. The major indigenous pathogens that have readily adapted to the new host are pine needle blight caused by *P. funerea* and pine needle cast caused by *L. conigenum* and *L. pinastri*. These two needle diseases are also among the most common diseases of *P. radiata* in *ex situ* plantations (Table 5). However, mortality caused by these needle diseases alone has been low. Usually moisture stress causes browning of needle tips or browning and drop of second year needles first before the weakened trees are attacked by the pathogens. During the drought in 2006, total rainfall in the six month growing season from April to October fell to between 280 mm and 421 mm in the dry river valley area according to local meteorological records. The combination of moisture stress and the needle diseases led to some mortality in young plantings of *P. radiata* and also local pine species. These defoliating pests and needle pathogens will certainly have a detrimental impact on the growth of the introduced *P. radiata*, but the impact will not be fatal to the long term success of *P. radiata* introduction in the dry river valley area for environmental plantings once rainfall improves.

The biological isolation of the dry river valley area and its distance from the native range and other growing areas of *P. radiata* in the world are of a great benefit in limiting the introduction of pests and diseases known to attack the species. With the ever increasing demand for imported logs in China, the natural protection can not be expected to last forever, especially when *P. radiata* has become one of the major species of imported timber

into the country (Chen 2004). The length of time elapsed since introduction but before detection enhances the chances of establishment of exotic pests and pathogens from other *P. radiata* growing countries. A good example is the introduction into China of the red turpentine beetle, *D. valens* LeConte, that frequently kills *P. radiata* trees in its native range in California (Smith 1971). Another is the burnt pine longhorn beetle, *Arhopalus tristis*, which has recently been intercepted on imported *P. radiata* logs from New Zealand at several trading ports in China (Li et al. 2006). To limit the introduction of exotic pests and diseases, tight quarantine and border control measures will have to be established and implemented. Preventing introductions is the first line of defence against non-native invasive species of forest insects and pathogens (Tkacz 2002). Strict quarantine laws and modern quarantine practices have helped to ensure forest health of *P. radiata* plantations grown in the Southern Hemisphere (Eldridge and Simpson 1987; Burgess and Wingfield 2001). However, such efforts can only be successful to the degree that the governments at different levels, industries, organisations and individuals coordinate to implement them (Owen 1997).

Conclusions and recommendations

We have identified some specific forest health risks to the long-term success of *P. radiata* introduction in the dry river valley area for environmental plantings. These risks are closely associated with the indigenous pests and pathogens of the native pines since they are considered more likely to establish on *P. radiata* over time. Exotic pests and pathogens are of a quarantine concern at present. Although detrimental to the survival and growth of the introduced *P. radiata*, the impact of identified forest health risks are not considered to be fatal to the long term success of *P. radiata* introduction in this area.

To minimise forest health risks the following recommendations will need to be adopted over time:

∗Establish a forest health survey team to appraise the pests and diseases, diagnose the causes, and study their biology, ecology and epidemiology in the *P. radiata* plantations as well as in the adjacent indigenous pine forests.

∗Exercise continuous surveillance of all *P. radiata* plantations for any new outbreaks of pests and diseases. Once a new outbreak eventuates, control measures should be adopted immediately to limit its spread, if eradication is not possible.

∗Approach the Chinese government to develop and implement quarantine procedures to restrict entry of germplasm or logs of *Pinus* species and *Pseudotsuga* species to only those countries known to be free from *F. circiuatum*, the pine pitch canker disease.

∗Learn from the incursion management plan for pine pitch canker in Australia and New Zealand by Gadgil et al. (2003) and if possible, adopt some measures in the plan.

∗Develop self-reliance in germplasm of *P. radiata* in Sichuan as quickly as possible to minimize the risk of introduction of pathogens on seeds sourced from other countries.

∗Develop internal quarantine procedures to restrict entry to Sichuan of pine logs to those Provinces known to be free from the introduced *D. valens* that frequently killed *P. radiata* in California.

Improvement of silvicultural practice can also help reduce forest health risks in the *P. radiata* plantations. The following improvements can be readily adopted by forest management:

∗Remove the plastic bags when *P. radiata* seedlings are placed in the pits during planting to allow root growth and development.

∗Reduce initial planting density to leave adequate space between trees in order to reduce moisture stress during dry periods of the year.

∗Keep weeds under control in the first 4–5 years after planting to minimise competition with the trees and encourage good air circulation around the base of the trees.

∗Thin older plantations with signs of stagnation due to high stand density and associated moisture stress. Remove suppressed trees and those more seriously affected by pine needle blight and needle cast in the stand during thinning. Then apply fertilizers to the thinned stands to improve tree vigour.

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